I. Introduction

This brief introduction is provided to orient the reader of this document. Recommended reviews of Martian meteorites include McSween (1985, 1994), Jagoutz (1991), and Swindle (1995).

This compilation of data on Martian meteorites is an attempt to introduce these rocks to new investigators. Meteoriticists are already familiar with most of this information. However, mineralogists, geologists, physicists or bacteriologists would have a hard time finding their way in this rather vast literature (~900 papers and abstracts since 1979) without some sort of catalog. Thus, this Mars Meteorite Compendium is a organized rock by rock, with brief mention to each important paper according to subject (petrology, isotopes, other). However, to be prudent, an investigator should look up the original work for the original data and full discussion of ideas. Every effort was made to have this compilation be entirely accurate, and the author would appreciate knowing where it is not — perhaps to be corrected in a future edition.

It was known as early as 1872 (Tschermak) that the Shergotty meteorite was a basalt that formed under relatively oxidizing conditions, but it wasn't until 1979 (Walker *et al.*, Nyquist *et al.*) that it became apparent to meteoriticists that the relatively young SNC* meteorites may have come from the planet Mars. This hypothesis was explained in detail by Wood and Ashwal in 1981, but it wasn't until Bogard and Johnson (1983) found gas trapped in glass in shergottite EETA79001 identical in composition to Martian atmosphere (as measured by Viking experiments), that it became widely accepted that SNC meteorites came from the planet Mars. Also in 1983, Clayton and Mayeda showed that SNC meteorites formed their own subgroup on an oxygen isotope diagram with their own fractionation line separate from that of the Earth or HED parent bodies. In 1984, Becker and Pepin found

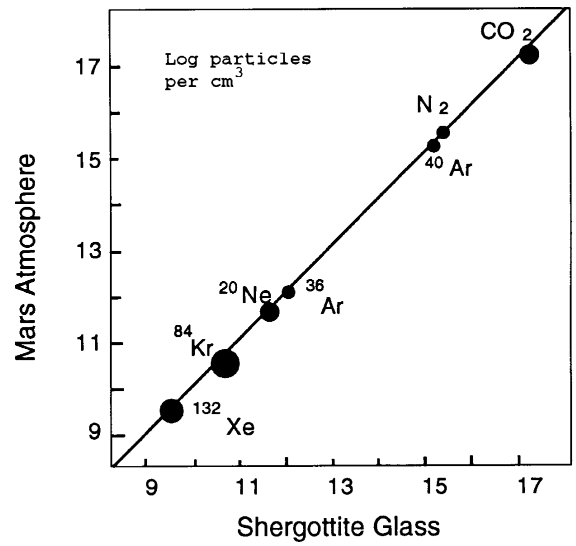

Figure I-1. *Log-log comparison of Viking-measured Mars atmosphere to trapped gases in EETA79001 glass. Figure from Pepin (1985), Nature* ***317****, 473.*

that nitrogen isotopes and N/Ar ratios were also typical of Viking results, clinching the argument (figure I-1). In 1995, Marti *et al.* found similar results in glass in a second SNC meteorite (Zagami).

Briefly, Martian meteorites are igneous rocks (basalts and cumulates) that have been shocked to various degree. However, they are not badly brecciated. Table I-1 gives the modal mineralogy. All, accept one (ALH84001), have young igneous ages. They were apparently blasted off Mars over the last 16 million years, judging from their cosmic-ray exposure ages. Several were seen to fall and were collected, others were recovered from the ice in Antarctica.

Recently, a sensation has occurred in the Press, over a paper published in Science by McKay *et al.* (1996), claiming possible evidence of fossil life on Mars, as determined by a study of one of the rocks (ALH84001) in this catalog. Indeed, the carbonates and associated PAHs, in this otherwise igneous rock, are unusual and require an explanation (McSween, 1996).

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*SNC is short hand for Shergotty, Nakhla and Chassigny, representative members of the three original major Martian meteorite types known. An explanation of acronyms is given in appendix 1.

Table I-1. Mineral modes of Martian meteorites.

	Chassigny	Valadares	Lafayette	Nakhla	Shergotty	Zagami	Zagami	ALH77005	ALH84001	EETA79001	79001B	LEW88516	Y793605	QUE94201
						coarse	fine			A	B			
olivine	88.5	minor	minor	15	0.3			60.2		8.9		45.9	35	
orthopyrox.	4		minor					9.5	97	5.4		25.3	60	52.3
clinopyrox.	3.8	major	major	78	71.5	80	74	3.7		65	59.5	12	tr.	
plagioclase	2.6			3.7	23	10	19	9.5	1	17	29.1	7	5	41.3
“chromite”	1.4				2.5	2.6	1.8	2.1	2			0.8		
Ti-magnetite				1.9						3	3.5			
ilmenite					0.25			0.5				0.2	tr.	2
sulphides				tr.	0.3	0.6	0.4	0.3				0.3		0.24
phosphate				tr.	1	1.3	0.6	0.4	0.15	0.2	0.4	0.9		2.4
carbonate									tr.					
mesostasis					1.2	3.7	3			0.1	0.7			1.7
inc melt.	0.3			tr.										
melt						0.9	0.9	13.7				7.7	(20-30)	
reference	Prinz74 Nehru83		Harvey92	Bunch75 Treiman	Smith79 Stolper79 Stoffler 86	McCoy92	McCoy92	Treiman94	Mittlefehldt	McSween83	McSween83	Treiman94	Mikouchi	Harvey96 McSween96
rock name	dunite	Clinopyx.	Clinopyx.	Clinopyx.	basalt	basalt	basalt	Lherzolite	orthopyx.	basalt ?	basalt	Lherzolite	Lherzolite	basalt
weathering	fall	fresh	museum	fall	fall	fresh	fall	A	A/B	Ae				Be
index *		brittle				0.19-								
grain size				0.5-1.0	0.46 mm	0.36 mm	0.24 mm						.5 to1mm	up to 3 mm
NTL (krad at250)									1.3 ‘ 0.1					
26Al (dpm/kg)									61 ‘ 2					

* Weathering index from Antarctic Met. Data Base: A= minor, B= moderate, e= evaporite deposites visible to naked eye.

Chemical and Isotopic Signature

Martian meteorites have their own distinct chemical and isotopic signatures. Perhaps the most useful are the isotopic differences. In particular, Clayton and Mayeda (1996), have shown that the SNC group of meteorites are distinguished by their unique oxygen isotopes, which follow a fractionation line distinct from that of the Earth and Moon or other classes of meteorites (figure I-2). This isotopic signature for oxygen is thought to be the result of incomplete mixing in the solar nebular cloud during nebular condensation and planet formation.

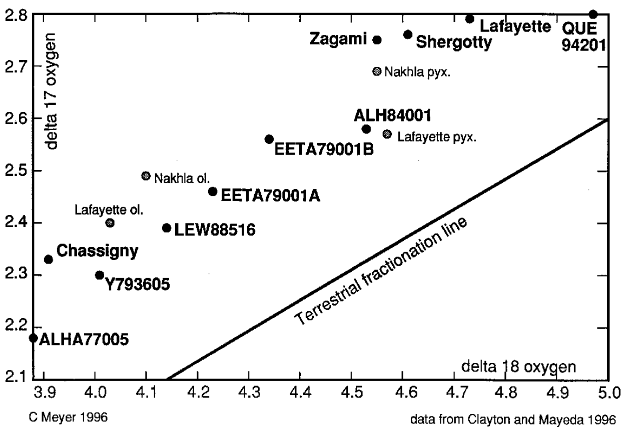

Figure I-2. Oxygen isotopic composition plotted as delta ^{17}O and ^{18}O for Martian meteorites and compared to terrestrial fractionation line. The data are from Clayton and Mayeda (1996).

Martian meteorites also have isotopic ratios of hydrogen, nitrogen and carbon that are heavy compared to the Earth, apparently due to atmospheric loss to space on Mars. These are recorded in certain portions of Martian meteorites that have interacted with the Martian atmosphere (figures I-3, I-4). Even Xe isotopes (124 to 136) show mass fractionation due to atmospheric loss (figure I-5).

There is also evidence that the planet Mars formed during the interval that ^{53}Mn ($\tau_{1/2}$ = 3.7 My) and ^{146}Sm ($\tau_{1/2}$ = 103 My) were alive (Lugmair *et al.*, 1996, Harper *et al.*, 1995) and this also leaves a measurable isotopic signature (figure I-6).

In 1979, Stolper pointed out the broad chemical similarity of Shergotty with terrestrial type basalts (figure I-7) . Only a few years later, using data from Martian meteorites, Dreibus and Wänke (1985) detailed the chemical signature of Mars as distinctly different from the Earth (figure I-8). They found that Mars as a planet has a relatively high abundance of

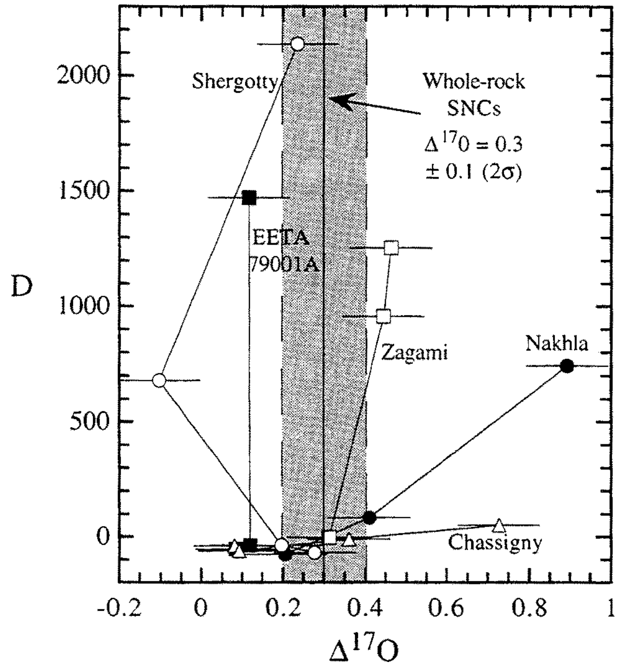

Figure I-3. Hydrogen and oxygen isotopic composition of water released from Martian meteorites. Diagram from Leshin et al. (1996a). LPI Tech. Rpt. 96-01, 31.

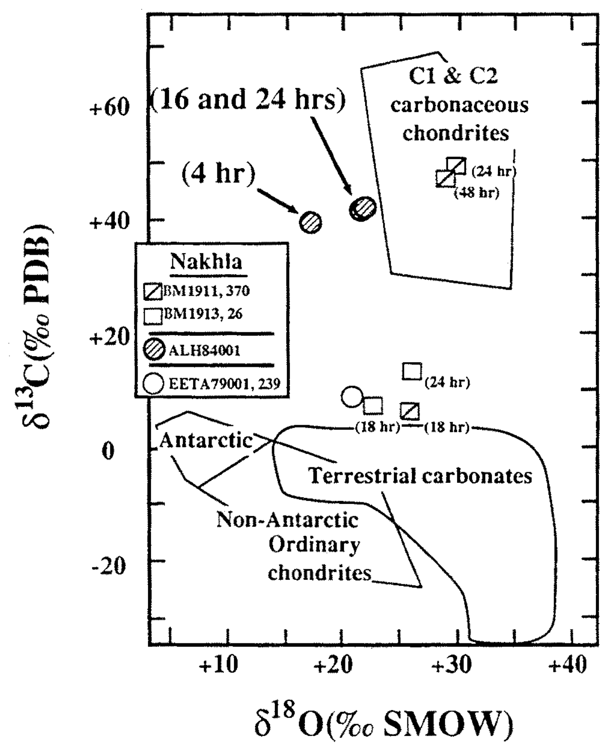

Figure I-4. Carbon and oxygen isotopic composition of carbonates in Martian meteorites. Diagram from Romanek et al. (1996). LPI Tech. Rpt. 96-01, 40.

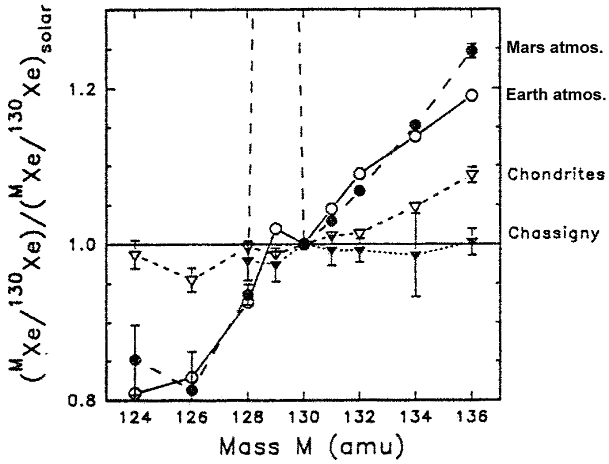

Figure I-5. *Xenon isotopic composition of atmospheric trapped Xe in EETA79001 normalized to solar wind Xe. Figure from Swindle (1995), AIP **341**, 175.*

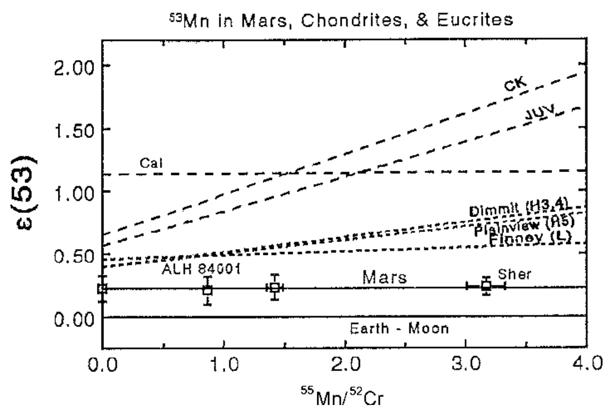

Figure I-6. *Isotopic composition of Cr in Martian meteorites compared with other solar system objects. Figure from Lugmair et al. (1996), Lunar Planet. Sci. XXVII, 786.*

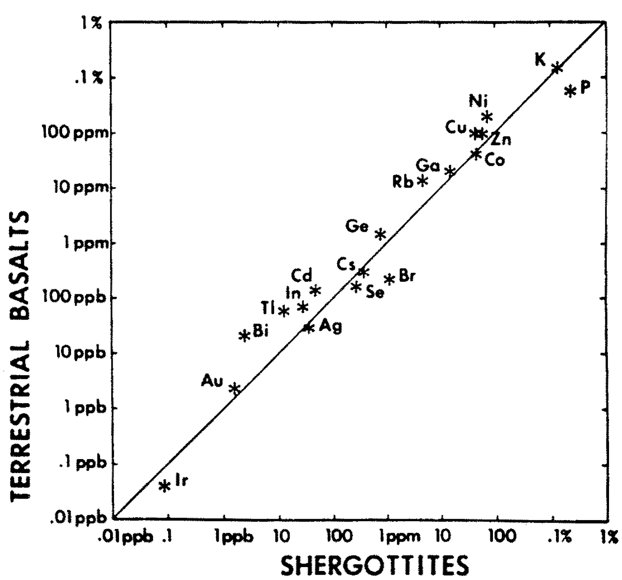

Figure I-7. *Comparison of average compositions of terrestrial basalts with averages for Shergottites as plotted by Stolper (1979), EPSL **42**, 239.*

volatile elements (figures I-9, I-10). This conclusion is also reached by an analysis of the U/Th/Pb systematics (Chen and Wasserburg, 1986a) which indicates a high Pb/U ratio for source region of basalts on planet Mars. Martian rocks also have an excess of ^{129}Xe, first seen by Rowe *et al.* (1966) and possibly explained by Musselwhite *et al.* (1991). These chemical and isotopic signatures, allow meteoriticists to group these rocks together. If one of these meteorites is from Mars, then they all are!

Mars Ejection Age

The length of time that a small rock spends in interplanetary space can be determined from its exposure to high-energy, cosmic-rays which cause measurable changes to some isotopic ratios (He, Ne, Kr). So far, five groupings of cosmic-ray exposure ages (figure I-11) have been recognized (Eugster *et al.*, 1996). Two explanations of these natural groupings are possible. On the one hand, these ages could be the result of different impacts on Mars. Or, less likely, a large parent object that was ejected from Mars at earlier time could have provided shielding from cosmic rays, until these meteorites were eject from it (Bogard *et al.*, 1984).

ANSMET

Six of the Martian meteorites have been found on clean ice in Antarctica. In 1969, Japanese explorers found an important concentration of meteorites on blue ice near the Yamato Mountains in Antarctica (Yoshida *et al.*, 1971). It took until 1976, for Bill Cassidy to get support from the National Science Foundation for a joint U.S.-Japan expedition to look for meteorites on ice within reach of the U.S. base at McMurdo. Since then, Japanese and U. S. teams with international participation, have returned thousands of meteorites from Antarctica (see Lipschutz and Cassidy, 1986; Cassidy *et al.*, 1992), including six from Mars. Antarctica remains the best hope for finding additional samples.

Figure I-12 shows how the ice builds up against the Trans-Antarctic Range where the katabatic winds erode the ice and leave concentrations of meteorites on the surface to be picked up by meteoriticists (figure I-13). The length of time that these meteorites have been in the ice sheet is determined by the decay of several different radionuclides produced by cosmic-ray exposure in space. ^{14}C and ^{36}Cl yield ages on the order of roughly 100,000 years.

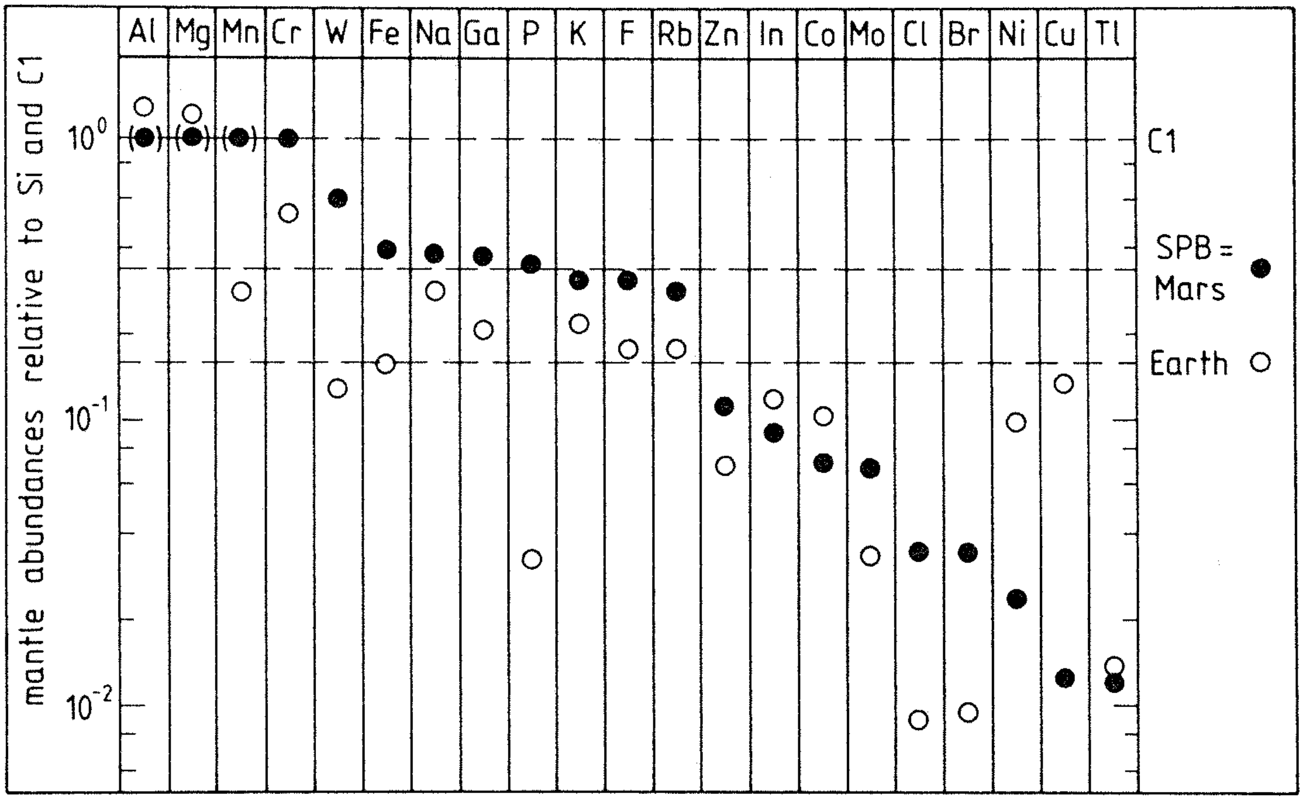

Figure I-8. *Comparison of major and trace element compositions of silicate portions of the Earth and Mars (figure by Longhi et al., 1992, in Mars, page 194), after Wänke and Dreibus, 1984.*

Weathering

Martian meteorites apparently have been exposed to weathering conditions on Mars as well as on Earth. Various kinds of 'salts' have been found in several Martian meteorites (see Gooding, 1992, for review). Gooding and his colleagues have shown that at least some of these weathering products were present before the fusion crust formed on the meteorites at the time of entry into Earth's atmosphere and, thus, must have formed in an extraterrestrial (Martian) environment.

However, to complicate matters, most meteorites collected in Antarctic are weathered to some degree during their stay on Earth (Gooding, 1989, Lipschutz, 1982). In fact, Fudali and Scutt (1989), observed liquid water and icicles on the lee and sun facing sides of boulders at Elephant Moraine and stated that *"liquid water may be a more pervasive weathering agent than previously supposed."* One must be able to distinguish between the two kinds of weathering.

Isotopic data are key to distinguishing which kind of weathering is dominant in a given sample. Using techniques of differential outgassing by heating, combustion or acid dissolution, various isotopic

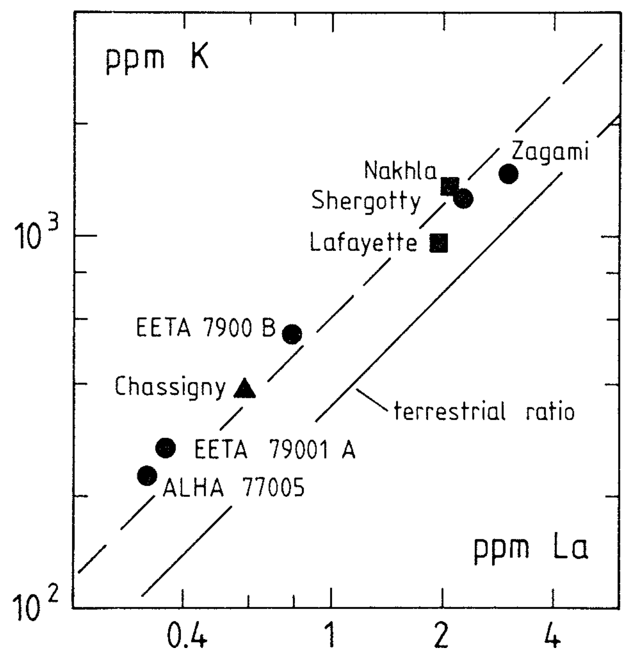

Figure I-9. *Comparison of compositions of K (moderately volatile) and La (refractory) for Martian meteorites and typical terrestrial rocks (figure by Longhi et al. (1992) in Mars, page 190).*

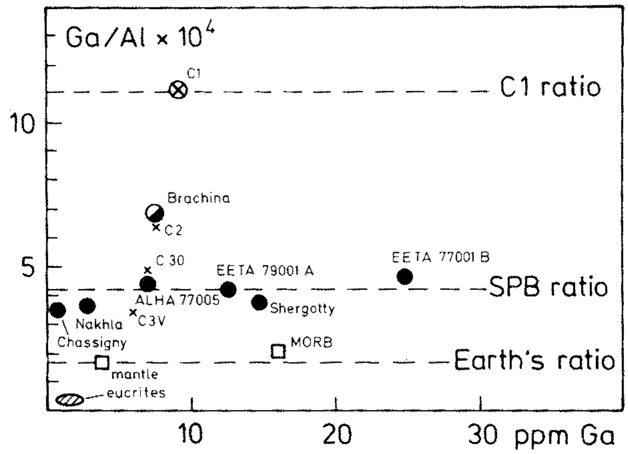

Figure I-10. *Comparison of Ga (volatile) and Al (refractory) compositions for Martian meteorites, terrestrial rocks and Eucrites. Figure from Nehru et al. 1983, Proc. 14th LPSC, page B241.*

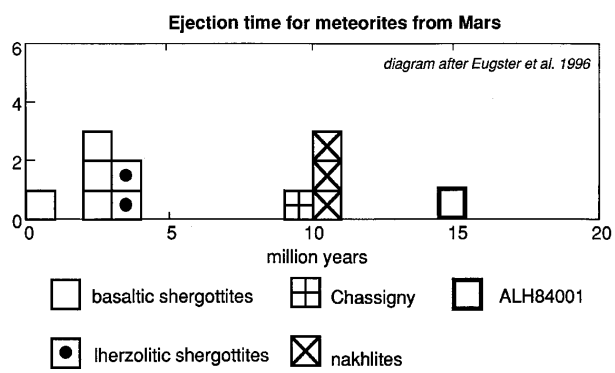

Figure I-11. *Figure summarizing the cosmic-ray exposure ages of Martian meteorites. Figure redrafted from Eugster et al. (1996), Lunar Planet. Sci. XXVII, 346.*

components have been isolated. In this regard, ^{14}C is a useful indicator of terrestrial weathering. Jull *et al.* (1996) have found that ^{14}C is correlated with other isotopic variations (figure I-14).

Karlsson *et al.* (1991) have shown that the hydrated Mg-carbonate nesquehonite forms rapidly on some meteorites found in Antarctica. The isotopic composition of carbon and oxygen ($\delta\ ^{13}C$ = 5.4 ‰ and $\delta\ ^{18}O$ = 9.4 ‰) of bicarbonate found on the chondrite LEW85320 is typical of Antarctic weathering (Jull *et al.*, 1996). Isotopic exchange reactions also must be considered. It is known that one isotope can exchange while leaving the others unchanged (Socki *et al.*, 1993).

Figure I-12. *High altitude photograph of Lewis Cliff Ice Tongue and Meteorite Moraine in Antarctica. USGS Photograph TMA999-044. As the ice slides off the continent it collides with the Trans Antarctic Mountain Range, where it wells up and is ablated away by the katabatic winds, leaving the meteorites concentrated on the blue ice fields adjacent to the mountain barriors. Thousands of meteorites (including rocks from the Moon and Mars) have been collected from these blue ice fields by American ANSMET and Japanese NIPR field parties.*

Figure I-13. *High altitude helicopter with three meteorites on blue ice during 1978 ANSMET (Antarctic Search for Meteorites) expedition led by Bill Cassidy to Allan Hills. NASA photo S78-28789.*

Martian Minerals

If one were to only consider the mode (table I-1), the mineralogy of Martian meteorites may seem relatively simple. However, a wide variety of minerals have been reported in this set of twelve Martian rocks (see a cross reference in table I-2). Many of these minerals have only been seen once and need to be verified. They may give a clue as to what we are likely to find when we finally get to Mars! Some are primary (amphibole, mica, carbonate). Others are weathering products (salts). Some are shock-produced (maskelynite, stishovite, ringwoodite).

Shock

In order to get rocks off the surface of Mars, one would think that they must be highly shocked during the impact. However, for really large impacts, Melosh (1984, 1985) pointed out that when a rebounding shock wave traveling from the interior, reaches a free (unsupported) surface, it will loft rocks off the planet surface. In this regard, it is interesting to note that Nakhla does not appear to have been highly shocked. Likewise, the delicate carbonates in ALH84001 do not appear to have been badly damaged. On the other hand, the basaltic shergottites (Shergotty, Zagami, ALHA77005, EETA79001, LEW88516, QUE94201 and Y793605) have all been modified by extreme shock pressures, as evidenced by maskelnitization of the plagioclase, fracturing, mosaicism, and undulatory extinction of the olivine and pyroxene, polysynthetic twinning in pyroxene, Fe oxidation in olivine and presence of melt pockets and veins (Stöffler *et al.*, 1986, Wadhwa *et al*., 1994). Shock also may have erased the original remnant magnetization.

World Location

Over the years, many trades have distributed the Chassigny, Nakhla, and Shergotty meteorites to museums and scientific institutions around the World (table I-3). Some samples, such as Zagami, have been obtained and sold by mineral dealers. Museums will want to exhibit these specimens because of public interest—and fees that they can charge for a showing. The recent history of the samples may prove as interesting as their geological history and the author is interested in obtaining information about which samples the research has been done on. This has not always been noted by the research scientist in their publication.

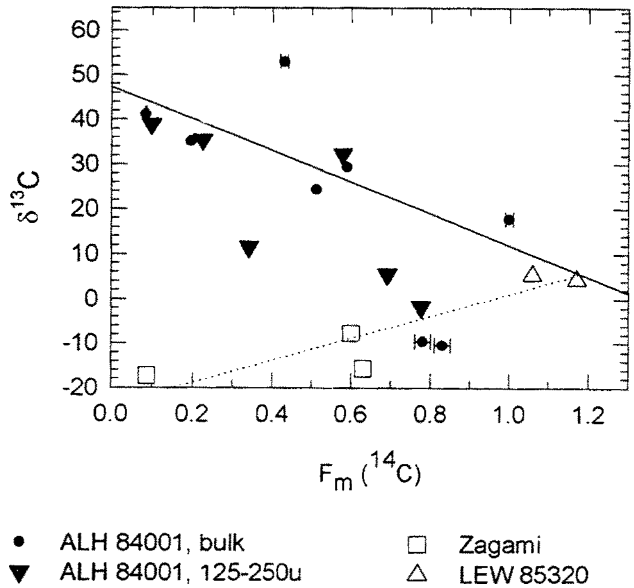

Figure I-14. *Dependence of ^{13}C and ^{14}C in CO_2 released by acid etching of Martian meteorites. Figure from Jull et al. (1996a). LPI Tech. Rpt. 96-01, 22.*

Preliminary Examination of Antarctic Meteorites

The original meteorite descriptions from the preliminary examinations of meteorites collected by ANSMET are published in the Antarctic Meteorite Newsletter (AMN) which is a periodical issued by the Meteorite Working Group to inform scientists of the basic characteristics of specimens recovered in the Antarctic. This can be obtained from the Planetary Materials and Missions Branch, Johnson Space Center. The Smithsonian Institution (USNM) also publishes meteorite descriptions and results of field investigations in their Smithsonian Contributions to the Earth Sciences. Some useful cross references to these sources are give in table I-4. During preliminary examination, Antarctic meteorites are assigned indices of weathering and fracturing (table I-5).

An explanation of acronyms and jargon is given in appendix I. The collection, curation and allocation process for the ANSMET meteorites is briefly diagramed in appendix II.

The locations of field areas where Martian meteorites have been found in Antarctica are given on page v. For more information on meteorites from Mars, see the website at: http://www-curator.jsc.nasa.gov.

Table I-2. Cross-index to minor minerals reported in Martian meteorites.
Caution: This table is incomplete and many of these minerals are unsubstantiated. Major minerals are given in table I-1.

	Nakhla	Lafayette	Gov. Val.	Shergotty	Zagami	Chassigny	ALHA77	ETTA79	ALH84	LEW88	QUE94
Hydrous phases											
biotite						jj,vv					
amphibole			pp	v,x,vv	x,oo,vv	l,jj,vv				ww	
"micabole"								aa,nn			
"iddingsite"	j,h,kk	rr	s								
smectite	ii,kk,nn										
"illite"								aa,nn			
ferrihydrite		rr									
FeO(OH)							o				
Sulfides											
greigite (?)									ggg		
chalcopyrite		i	n,s								
pyrite	i	k	n,s						yy,hhh		iii
pyrrhotite				p,q			xx	u,w	ggg	mm,ss,ww	ooo
pentlandite						l	xx	w			
marcasite						l					
troilite (?)	m	k				l	o,y				
ZnS									eee		
Oxides											
magnetite	m	i,k	n,pp	a,d,p,q					fff,ggg		
maghemite		rr									
ilmenite				p	q		o				ooo
chromite						b,l	o,xx	u,w	yy	qq,ww	
ulvospinel				q	q			u			ooo
"Fe, Al spinel"			pp	x	x						
rutile						l					
baddeleyite				p,ee		l					ooo
"silica"									nnn		ooo
SiO2			n	p,q				w,t			
stishovite (?)				z							
cristobalite				d			ff			qq	
Feldspars											
albite						jj					
K-rich feldspar	i	i,k		p		l					
maskelynite				a-d,z	q,uu		o,hh			qq	
Phosphates											
apatite	i,r			q,ee	uu,vv	l		u	yy,ggg	qq	jjj ooo
whitlockite				e,g,q,ee	oo,uu,zz		xx,hh	u,bb,ee		qq,ww	kkk ooo

	Nakhla	Lafayette	Gov. Val.	Shergotty	Zagami	Chassigny	ALHA77	ETTA79	ALH84	LEW88	QUE94
Unusual glass											
"opx. glass"									fff		
Si-rich glass	i,pp	s,rr		f,p,q					fff		ooo
"Pl. glass"							xx,z				
Carbonates									ggg		
calcite						bbb		aa,dd	ccc,nnn		
"ankerite"									ddd		
magnesite						bbb			yy,aaa,ccc		
sideroite	gg								nnn,ccc		
"dolomite"									nnn		
Other "salts" *(see Gooding 1992 for summary)*											
gypsum (?)	gg,ii					bbb		dd	eee		
epsomite (?)	ii										
NaCl	gg,ii										
Mg-phosphate								dd			
Fe-sulfate									eee		
Fe-K-sulfate											lll,mmm
Unusual mafic minerals											
fayalite				p,q	tt,uu,zz						lll, ooo
pyroxferroite				p				w			ooo
merrillite (?)				p							
ringwoodite (?)								u			
majorite (?)								u			

References
(a) Tschermak 1872, (b) Tschermak 1885, (c) Michel 1912, (d) Duke 68, (e) Fuchs 1962, (f) Binns 1967, (g) Fuchs 1969, (h) Ashworth & Hutchison 1975, (i) Bunch & Reid 1975, (j) Reid & Bunch 1975, (k) Boctor et al. 1976, (l) Floran et al. 1978, (m) Weinke 1978, (n) Berkley et al. 1979, (o) McSween et al. 1979a, (p) Smith & Hervig 1979, (q) Stolper & McSween 1979, (r) Crozaz 1979, (s) Berkley et al. 80, (t) Reid & Score 1981, (u) Steele & Smith (also Smith & Steele) 1982, (v) Treiman 1983, (w) McSween & Jarosewich 1983, (x) Treiman 1985a, (y) McSween 1985a, (z) Stöffler et al. 1986, (aa) Gooding & Muenow 1986, (bb) Nevle 1987, (cc) Berka & Holloway 1988, (dd) Gooding et al. 1988, (ee) Lundberg et al. 1988, (ff) Jagoutz 1989, (gg) Chatzitheodoridis & Turner 1990, (hh) Lundberg et al. 1990, (ii) Gooding et al. 1991, (jj) Johnson et al. 1991, (kk) Treiman & Gooding 1991, (ll) Longhi 1991, (mm) Dreibus et al. 1992, (nn) Gooding 1992, (oo) McCoy et al. 1992, (pp) Harvey & McSween 1992d, (qq) Harvey et al. 1993, (rr) Treiman et al. 1993, (ss) Harvey & McSween 1993, (tt) McCoy et al. 1993, (uu) Wadhwa et al. 1993, (vv) Watson et al. 1994a, (ww) Treiman et al. 1994a, (xx) Ikeda 1994, (yy) Mittlefehldt 1994a, (zz) Wadhwa et al. 1994, (aaa) Romanek et al. 1994a, (bbb) Wentworth & Gooding 1994, (ccc) Harvey & McSween 1995, (ddd) Treiman 1995b, (eee) Wentworth & Gooding 1995, (fff) Thomas et al. 1996, (ggg) McKay et al. 96, (hhh) Shearer et al. 1996b, (iii) McSween & Eisenhour 1996, (jjj) Mikouchi et al. 1996, (kkk) Wadhwa & Crozaz 1996, (lll) Harvey et al. 1996, (mmm) Wentworth & Gooding 1996, (nnn) Harvey & McSween 1996, (ooo) McSween et al. 1996.

Table I- 3. World location of Martian meteorites (weight in grams).
(caution: this is not complete - see totals)

	London BM(NH)	Wash. USNM	NewYork AMNH	Paris	Berlin	Vienna	Cairo	Calcutta	Chicago Field	Rome	Tempe UA	Russia	Other	Year	orig. weight (grams)
Nakhla	667+9 641 313 110 156+17	644	58	291 118 34	171	500	1,813 1,651 1,318 431 393 29	24	24	155	2.8 34	80.6	Harvard 159 Tokyo 134 Canberra 123 Stockholm 116 Oxford 51 Dublin 50 UCLA 78	1911	10,000
Lafayette	35	637							81		27		Kankakee 20	1931	800
Governor Valadares	6.4									97				1958	158
Shergotty	130	270	39	91 24 2	4	190		3,676	37	1	1.7	23.3	Budapest 77^ Canberra 3 ABQ 4	1865	5,000
Zagami	234	23	169	233	287								Nigeria ? Haag 2,800 ABQ NM 334 Japan 1,000 Kankakee 200	1962	18,000
Chassigny	66	23		215 118 41	13	104		7.7	6.7	24	0.4 6.5	22 +	Dublin 24 Oslo 18 Ottawa 5	1815	4000*
ALHA77005													Houston Japan 212		480
ALH84001		213											Houston		1,930
EETA79001		505											Houston		7,900
LEW88516													Houston		13
QUE94201													Houston		12
Y793605													Japan		18

^ lost in 1956 * today 600
compiled by C Meyer 1996

Table I-4. References to original rock descriptions (preliminary examination).

	AMN	Smith Inst.	
ALHA77005	1(2),9 1(3) 4(1),12 8(2),42 13(1),13	23,39	30,48
ALH84001	8(2),5 13(1),40 16(1),3	30,29	
EETA79001	3(3),4 4(1),133 8(2),42 9(1) 13(1),51	24,45	
LEW88516	14(2),19		
QUE94201	18(2),20		

AMN = Antarctic Meteorite Newsletter (volume, page)
Smith Inst. = Smithsonian contributions to the Earth Sciences (number, page)

Table I-5. Weathering and fracturing categories.

"Weathering" Categories:

A: Minor rustiness; rust haloes on metal particles and rust stains along fractures are minor.
B: Moderate rustiness; large rust haloes occur on metal particles and rust stains on internal fractures are extensive.
C: Severe rustiness; metal particles have been mostly stained by rust throughout.
e: Evaporite minerals visible to the naked eye.

"Fracturing" Categories:

A: Minor cracks; few or no cracks are conspicuous to the naked eye and no cracks penetrate the entire specimen.
B: Moderate cracks; several cracks extend across exterior surfaces and the specimen can be readily broken along the cracks.
C: Severe cracks; specimen readily crumbles along cracks that are both extensive and abundant.